LA-UR-20-23938
Approved for public release; distribution is unlimited.

Title: Heavy flavor and jet studies for the future Electron-Ion Collider

Author(s): Li, Xuan

Intended for: The 10th edition of the Hard and Electromagnetic Probes International Conference series, 2020-06-01/2020-06-05 (Austin, Texas, United States)

Issued: 2020-06-04 (rev.1)

LA-UR-20-23998

Heavy flavor and jet studies for the future Electron-Ion Collider

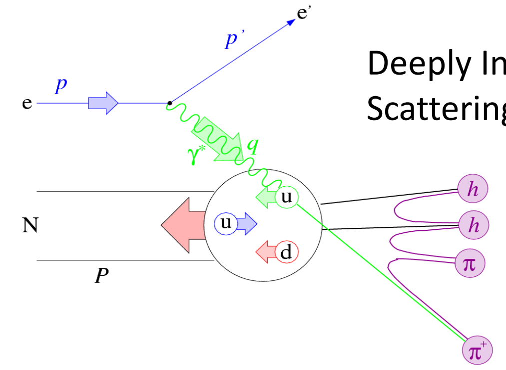
Xuan Li (xuanli@lanl.gov)
Physics Division, Los Alamos National Laboratory

Outline

- Introduction to the Electron-Ion Collider (EIC).
- New physics opportunities at the EIC: heavy flavor and jet studies.
    - Key EIC physics observables to explore the hadronization/fragmentation process.
    - Projection of the proposed heavy flavor measurements.
- Summary and Outlook.

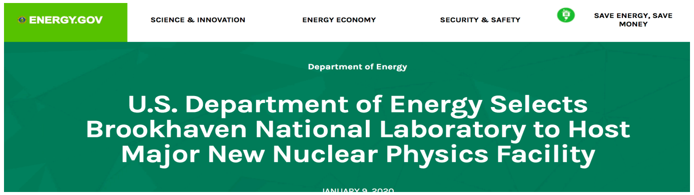
New QCD frontier: the Electron Ion Collider (EIC)

- The proposed Electron-Ion Collider (EIC) will bring new opportunities to answer fundamental questions in the high-energy nuclear physics field.

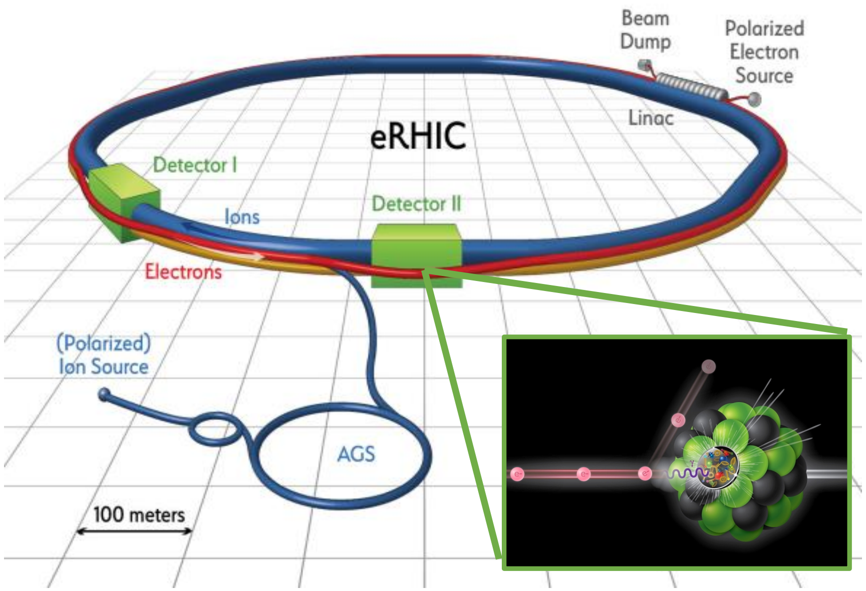


Deeply Inelastic Scattering (DIS)

- EIC CD0 announced and the site is selected to be BNL.

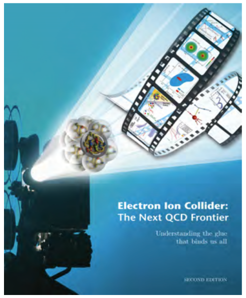


- e-N collisions at the EIC:
  - (Polarized) p, d/^{3}He beams at 20-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$.
- e-A collisions at the EIC:
  - Multiple nuclear species (A=2-208) and variable center of mass energies.
  - Luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$.

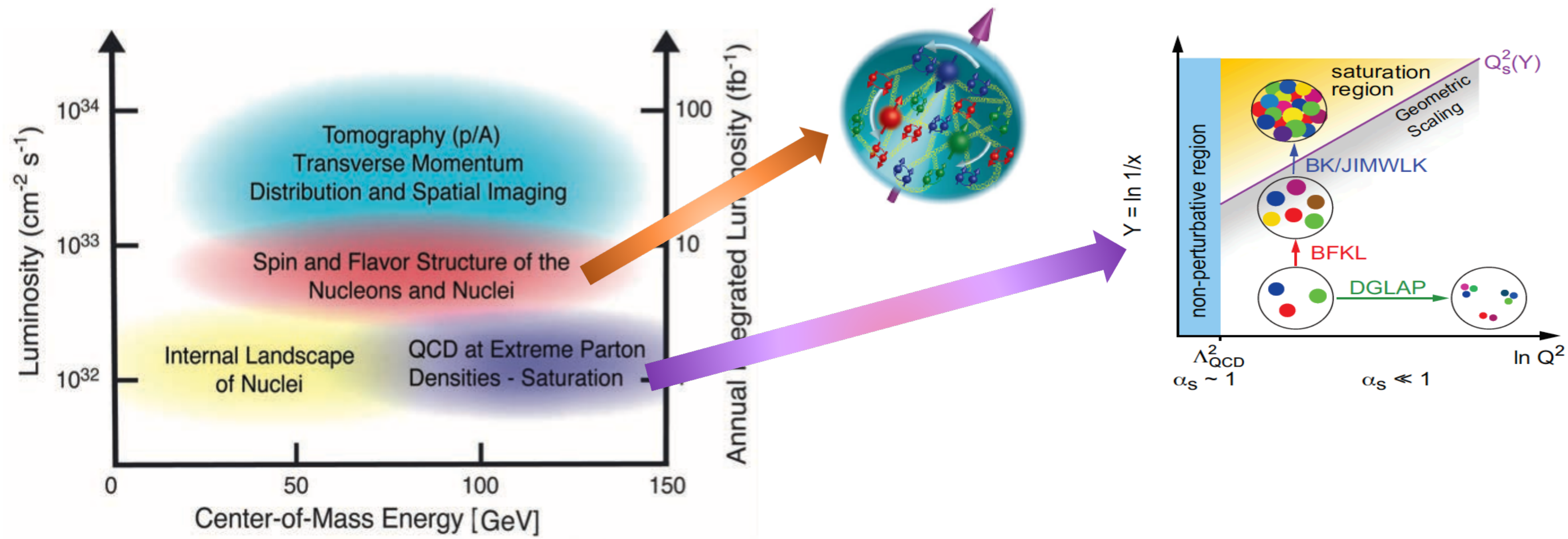


EIC science from the white paper

- EIC can help solve different fundamental physics problems in a wide x and Q^2 kinematic region.
  - How quarks and gluons distributed in momentum and space within the nucleon and heavy nuclei?
  - Proton spin origin?
  - What happens to the gluon density in nuclei, does it saturate at high energy?

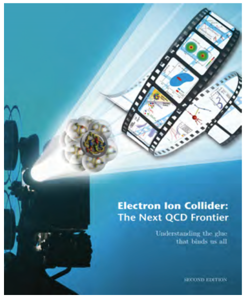


A. Accardi et al, **Eur. Phy. J. A**, 52 9 (2016).

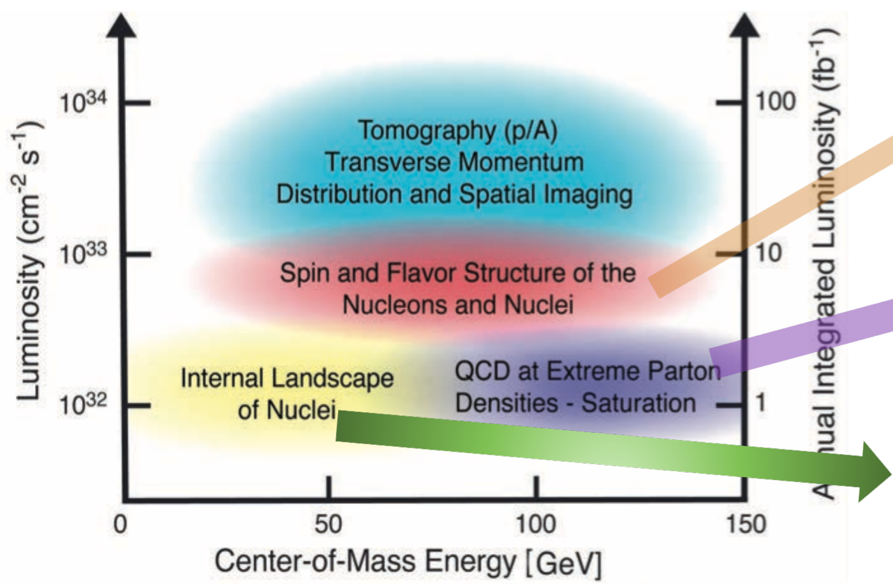


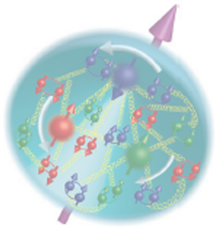
EIC science from the white paper

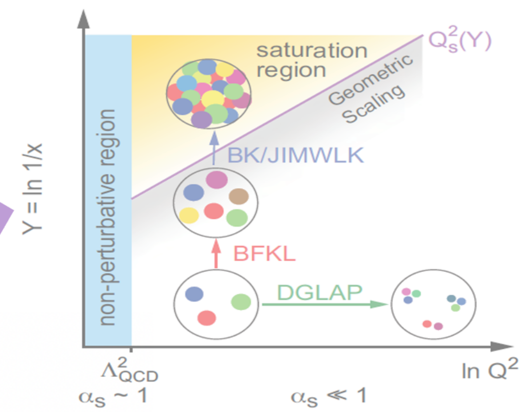
- EIC can help solve different fundamental physics problems in a wide x and Q^2 kinematic region.
  - How quarks and gluons distributed in momentum and space within the nucleon and heavy nuclei?
  - Proton spin origin?
  - What happens to the gluon density in nuclei, does it saturate at high energy?
  - A clean environment to study the hadronization and fragmentation process inside the nuclear medium.

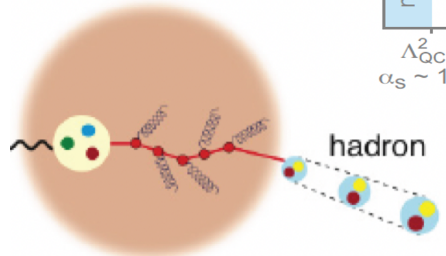


A. Accardi et al, **Eur. Phy. J. A**, 52 9 (2016).







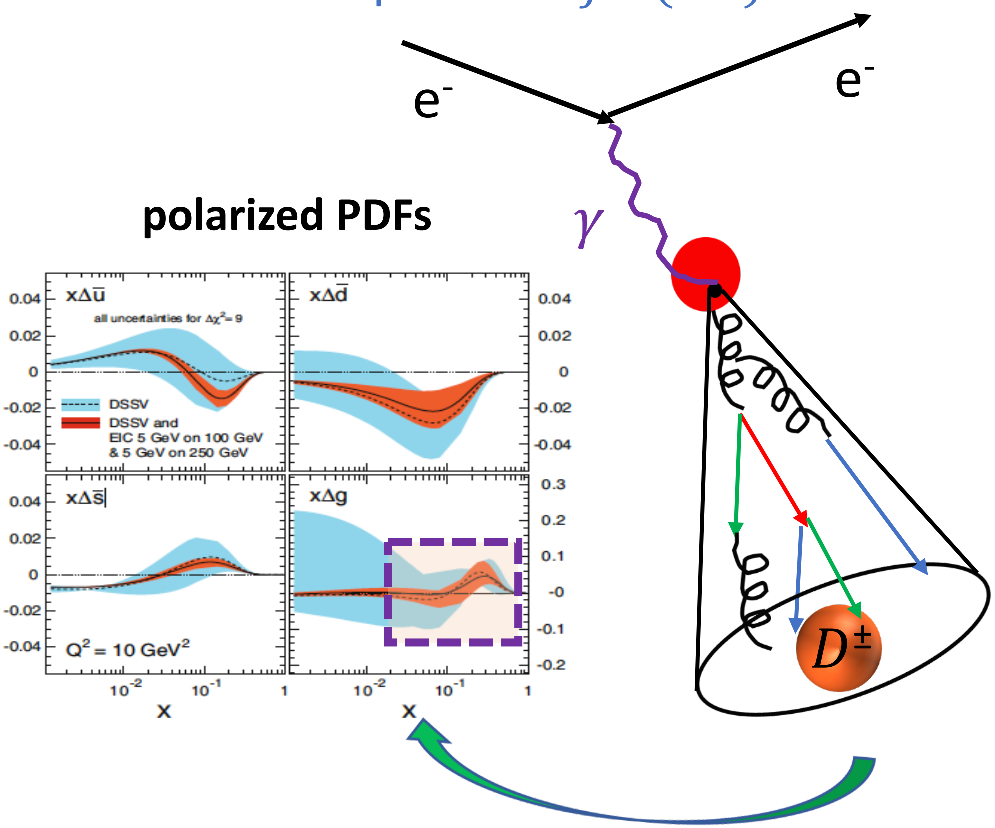


EIC golden channels: heavy flavor and jet probes (I)

- Through measuring heavy flavor hadrons, jets which can be treated as surrogates of initial quarks/gluons and their correlations in the hadron/nuclei going (forward) direction at the EIC.

[arXiv:1610.08536](https://arxiv.org/abs/1610.08536) **Phys. Rev. D 96, 114005 (2017)**

$$e^- + \mathrm{p} \rightarrow e^- + jet(D^{\pm}) + X$$



- To precisely determine the initial quark/gluon distribution functions in the poorly constrained kinematic region.
- To precisely study the quark/gluon fragmentation and hadronization processes.
- To provide further information on the gluon Sivers function and other spin observables.

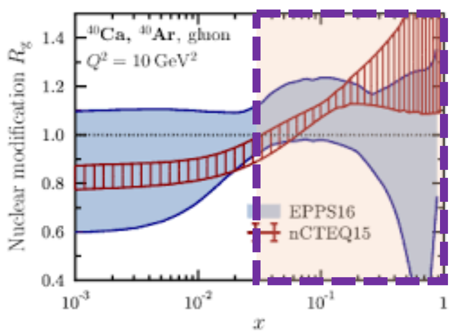
EIC golden channels: heavy flavor and jet probes (II)

- Measurement of heavy flavor hadrons, jets which can be treated as surrogates of initial quarks/gluons and their correlations in the hadron/nuclei going (forward) direction at the EIC.

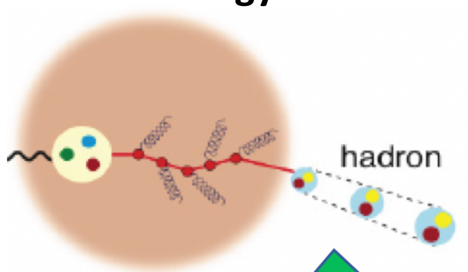
arXiv:1610.08536 Phys. Rev. D 96, 114005 (2017)

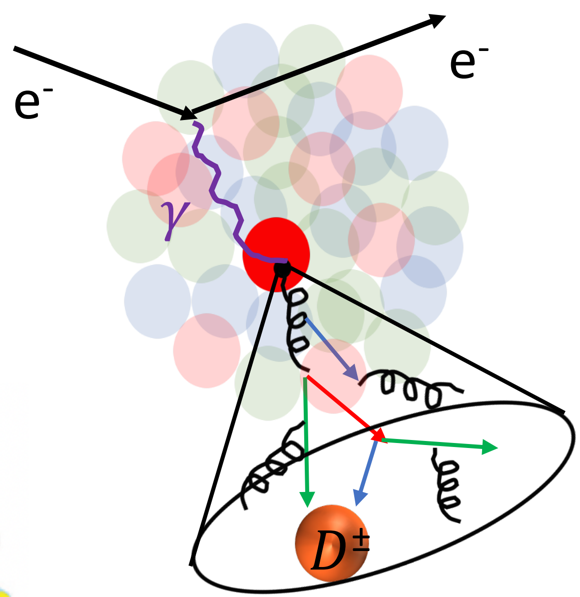
arXiv:2002.05880 $e^- + \mathrm{Au} \rightarrow e^- + jet(D^\pm) + X$

nPDF modification



Parton energy loss



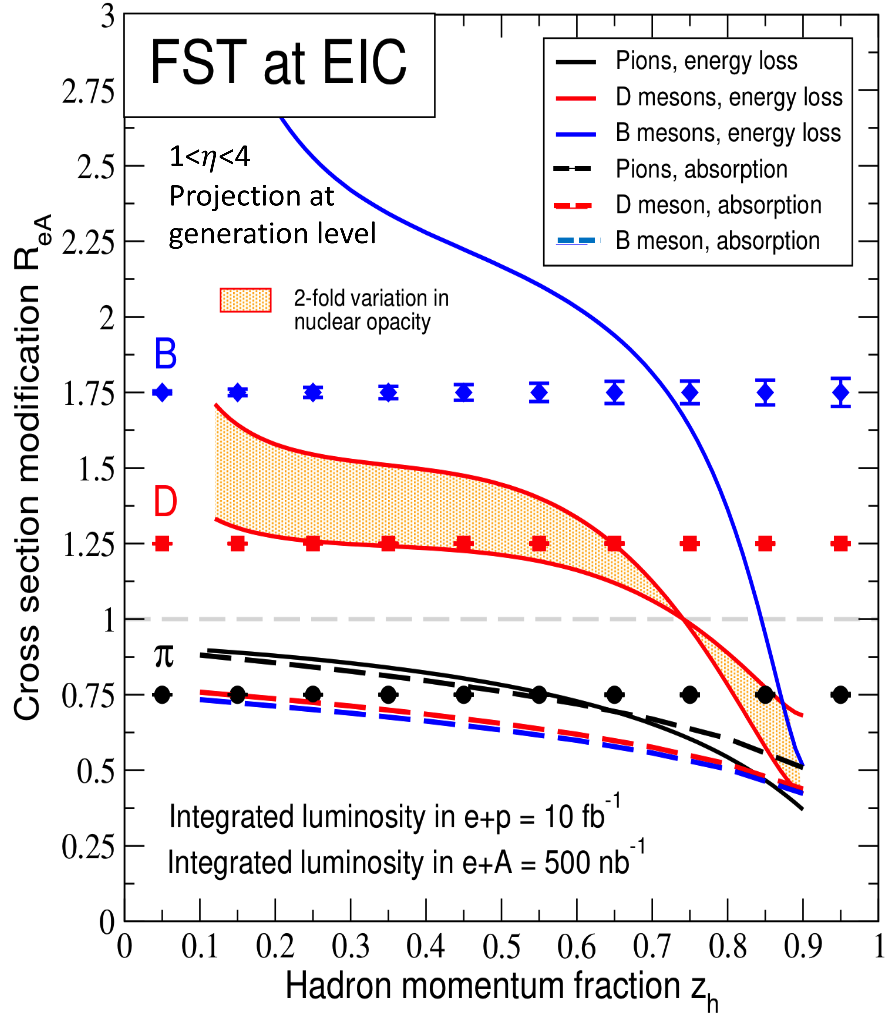


- To understand the nuclear medium effects on hadron production such as modification on nuclear PDFs, parton energy loss mechanisms and hadronization processes through the comparison of measured heavy flavor hadron/jet cross section between e+p and e+A collisions.

Key EIC physics observables are under study

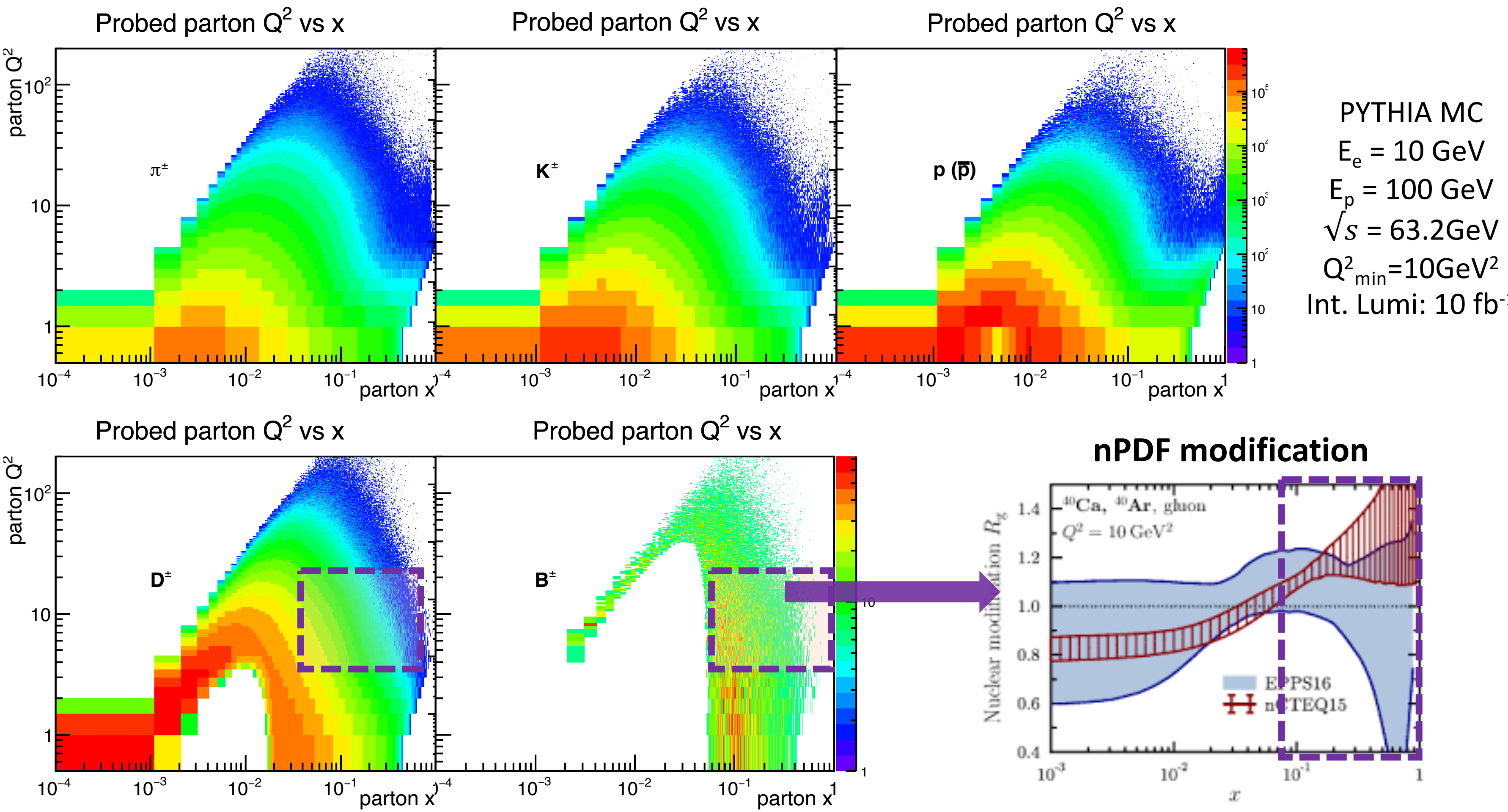
- Competing models of nuclear modification in DIS reactions with nuclei (e.g HERMES data). Differentiation not possible with light hadrons.
  - Hadronization inside nuclear matter (dashed lines).
  - Energy loss of partons, hadronization outside the medium (solid lines).
- Heavy mesons have very different fragmentation functions and formation times
  - Easy to discriminate between larger suppression for D/B mesons (in-medium hadronization) and strong/intermediate z enhancement (E-loss).
  - Enhanced sensitivity to the transport properties of nuclei.

arXiv:2002.05880



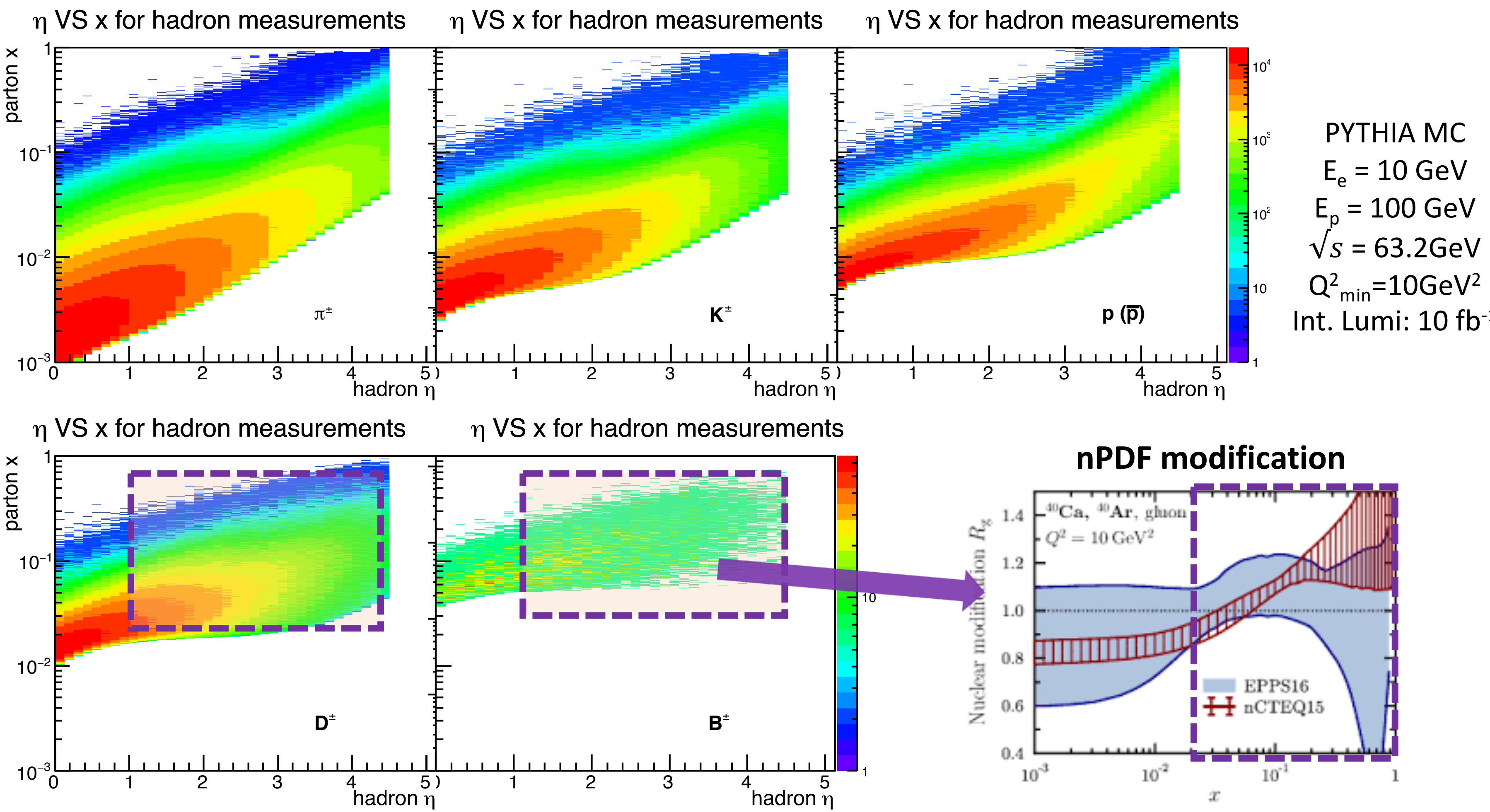
Future EIC measurements can access a wide kinematic phase space

- Future EIC heavy flavor measurements can access the high x region and provide better constraints on the (nuclear) parton distribution functions in this region.



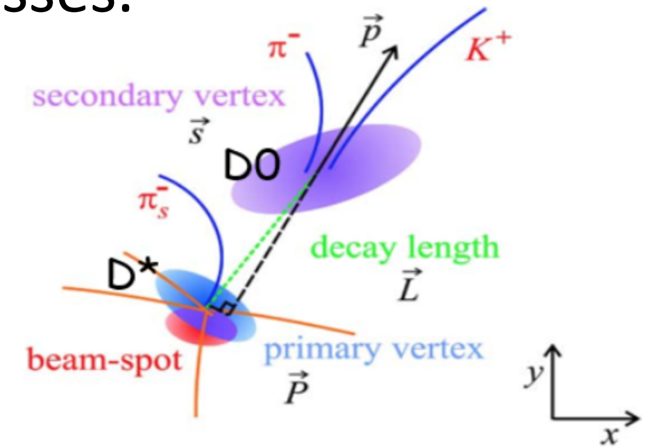
Future EIC measurements can access a wide kinematic phase space

- Forward heavy flavor measurements can access higher x region than the mid-rapidity measurements.



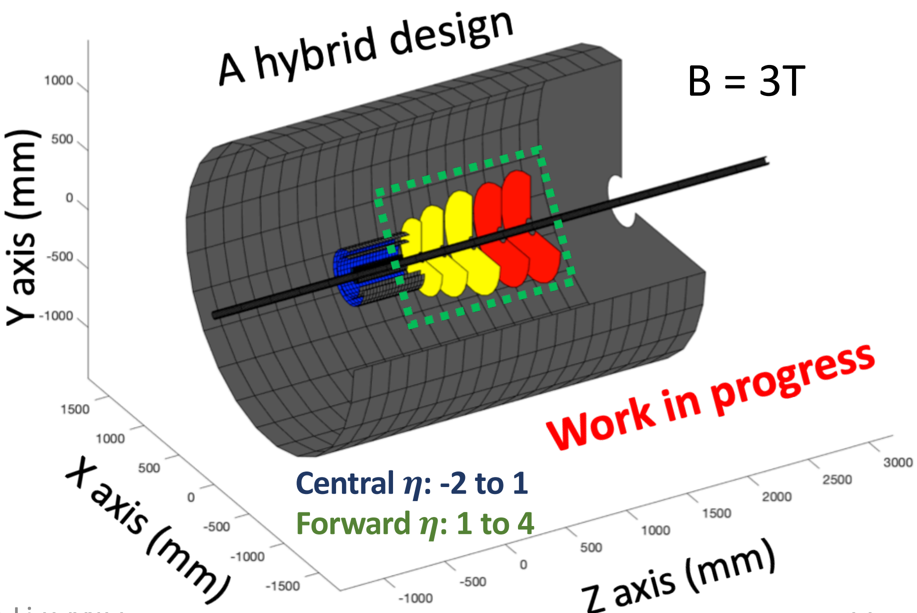
Critical detector to realize heavy flavor measurements

- At EIC, hadrons or jets which contain heavy quarks can be measured by detectors based on their unique lifetime and masses.



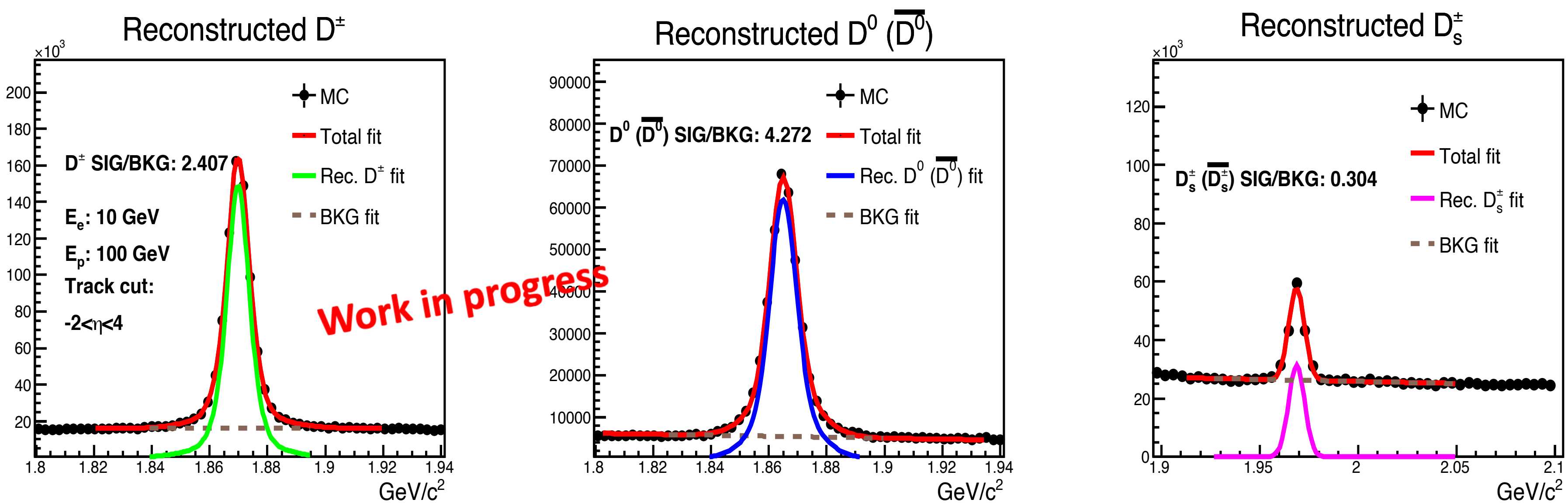
Particle	Mass (GeV/c^2)	$c\tau$ decay length
$D^\pm$	1.869	312 micron
D^0	1.864	123 micron
$B^\pm$	5.279	491 micron
B^0	5.280	456 micron

- To measure heavy flavor hadrons, jets and their correlations in the hadron/nuclei going (forward) direction at the EIC, a silicon central vertex and forward silicon tracking (FST) detector are needed.



Heavy Flavor reconstruction at the EIC (I)

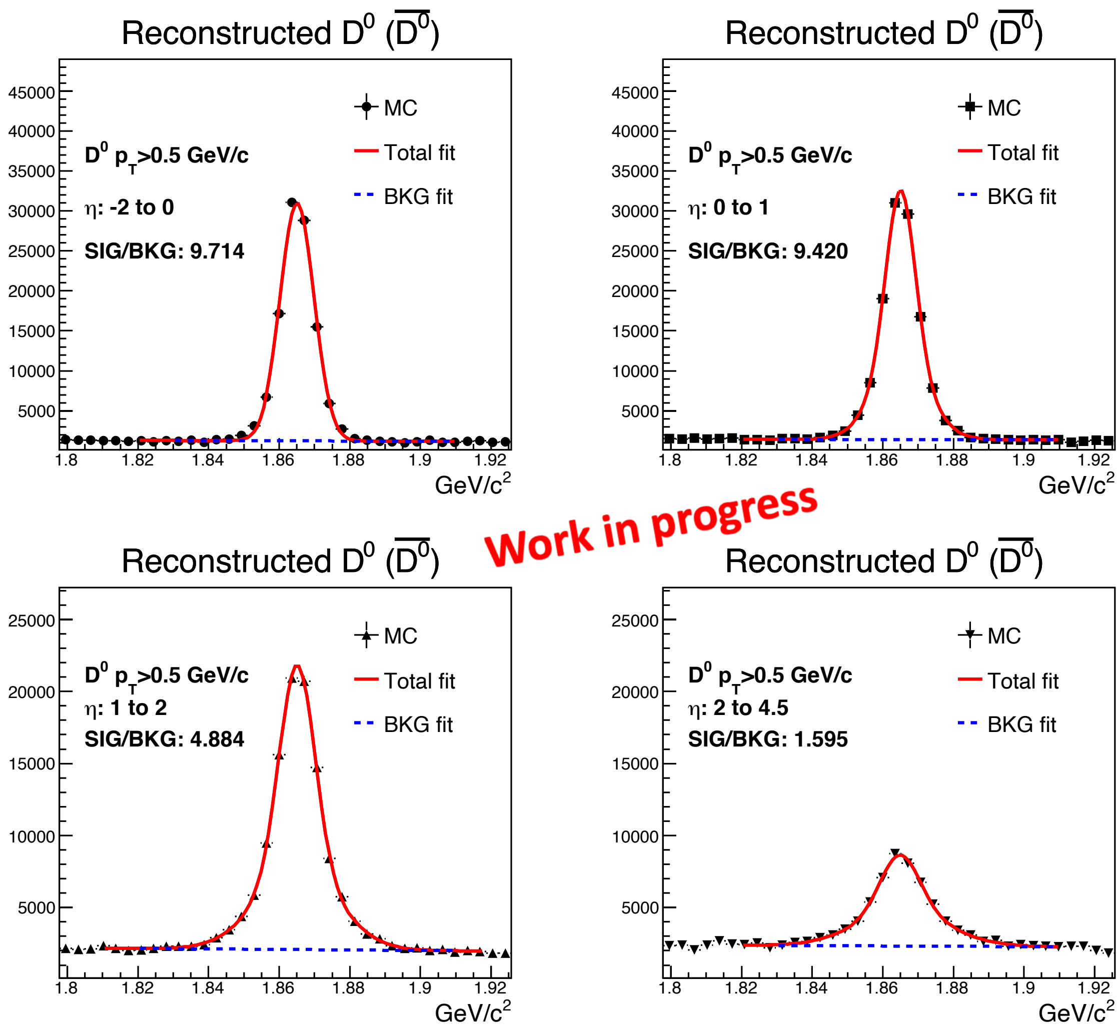
- PYTHIA simulation for 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.
- Reconstructed D meson mass distributions.
  - Primary vertex resolution: 20 μm.
  - Tracking η cut: -2 to 4 and track efficiency set at 95%.
  - Tracking performance implemented in the simulation.
  - 80% K/π/p separation is implemented.
  - Charged track clusters that contain $K^{\pm}$ with a decay length (DCA) cut.



- Clear D-meson signal can be determined from combinatorial background with one of the initial silicon tracker designs.

Heavy Flavor reconstruction at the EIC (II)

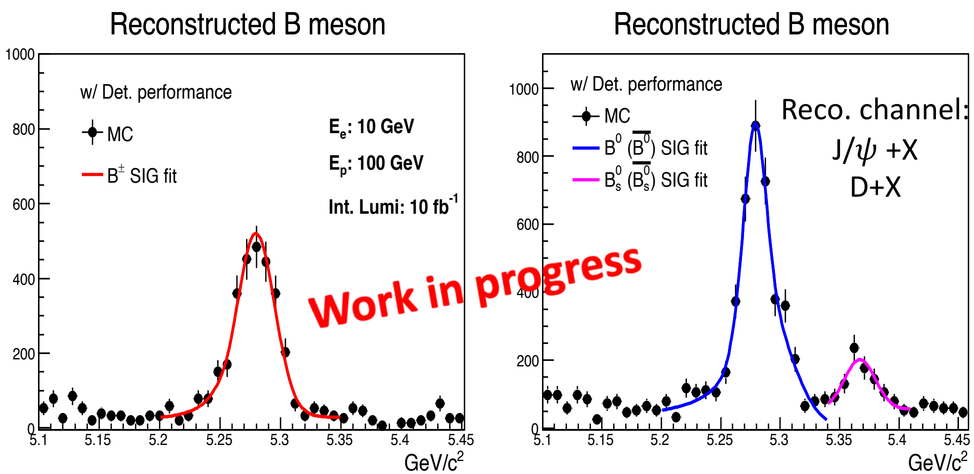
- Reconstructed D^0 ($\overline{D^0}$) meson mass distributions in different pseudorapidity η regions.



- Smaller signal over background ratio for more forward D^0 ($\overline{D^0}$) reconstruction mainly due to the pseudorapidity dependent tracking momentum resolutions.
- Optimization of the forward silicon tracker is underway to improve the reconstruction purity.

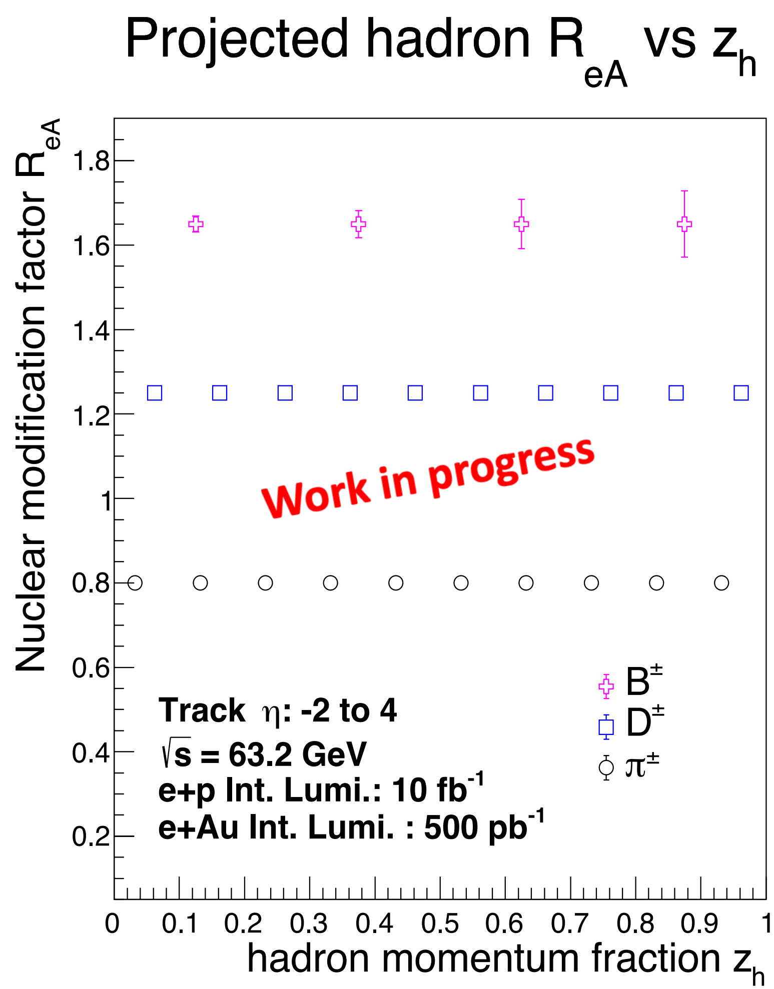
Flavor dependent nuclear modification factor projections for reconstructed hadrons

- Reconstruction of other heavy flavor hadrons, e.g. $B^{\pm}$.



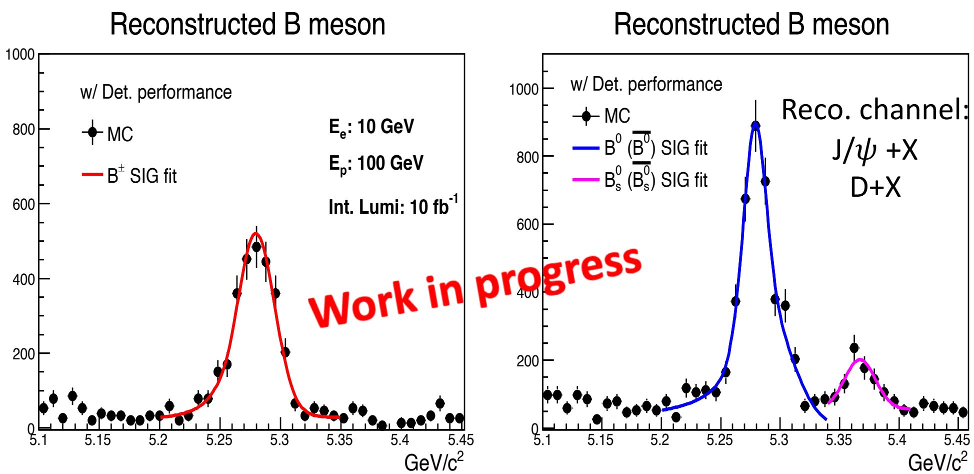
- The statistics of reconstructed hadron yields can help separate different models of the nuclear modification on hadronization processes.
- Heavy flavor measurements at the EIC will enhance the sensitivity of the nuclear transport properties.

Stat. uncertainty based on reconstructed hadron yields



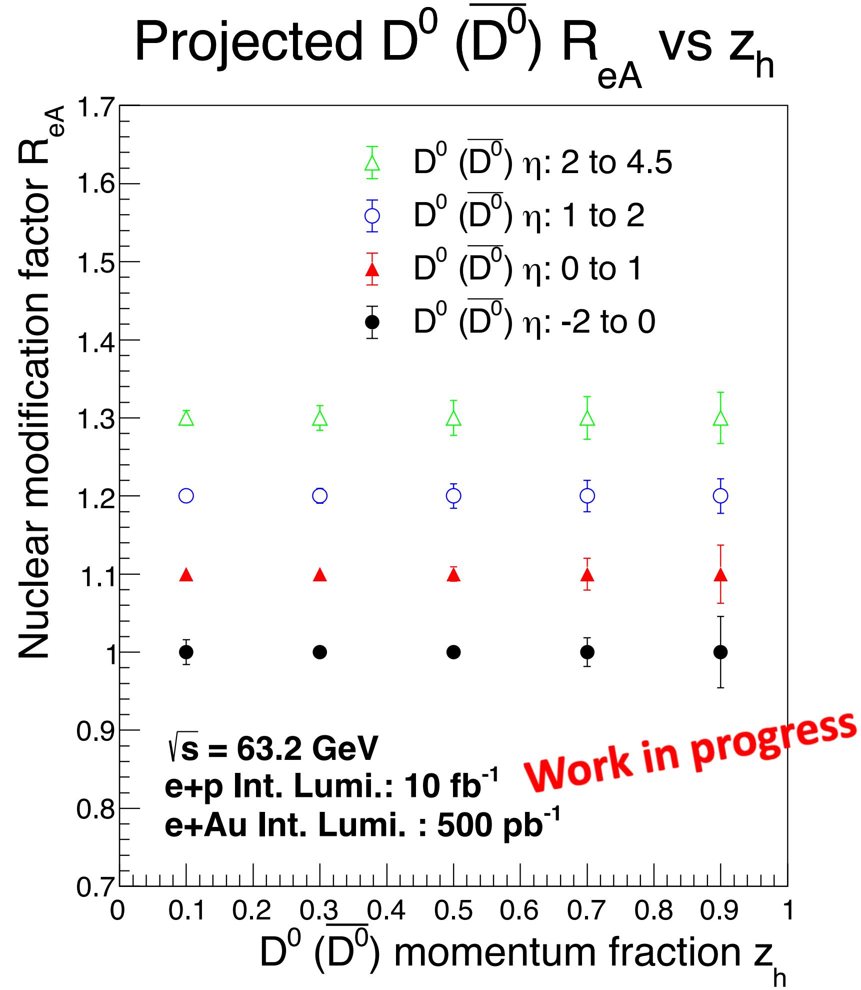
Flavor dependent nuclear modification factor projections for reconstructed hadrons

- Reconstruction of other heavy flavor hadrons, e.g. $B^{\pm}$.



- The statistics of reconstructed hadron yields can help separate different models of the nuclear modification on hadronization processes.
- Heavy flavor measurements at the EIC will enhance the sensitivity of the nuclear transport properties.

Projection for reconstructed D^0 ($\overline{D^0}$) yields in different η



Exotic studies at the EIC

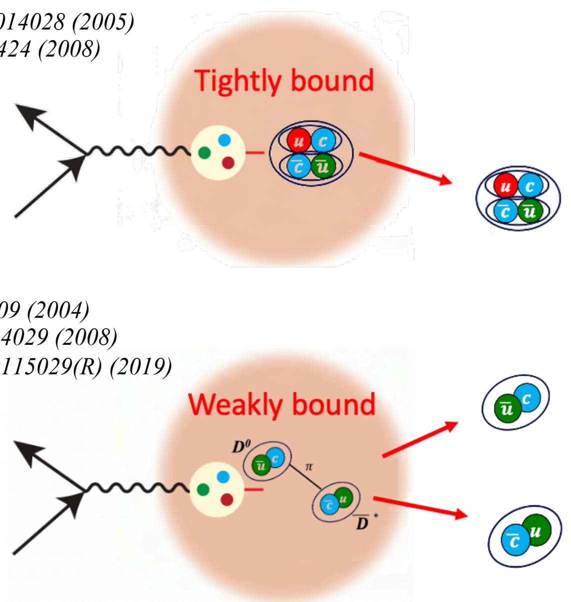
- Low beam background at the EIC enables precise studies of different quarkonium states such as J/ψ, ψ(2s) and exotic hadrons.

LHCb-CONF-2019-005, arXiv:2002.01551

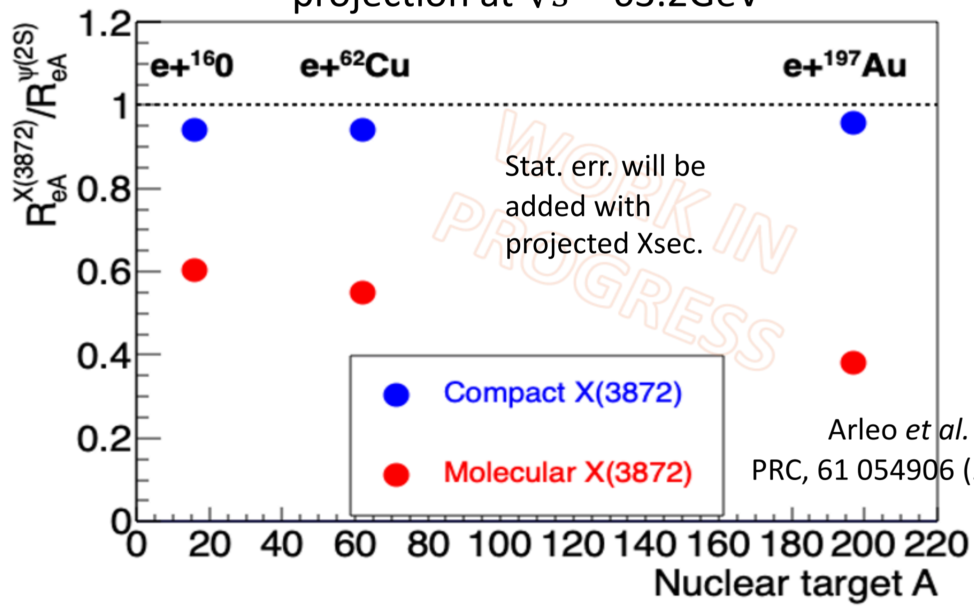
- Structure of new exotic hadrons can be explored by measuring their suppression in e+A collisions, e.g. X(3872).

PRD 71, 014028 (2005)
PLB 662 424 (2008)

PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV

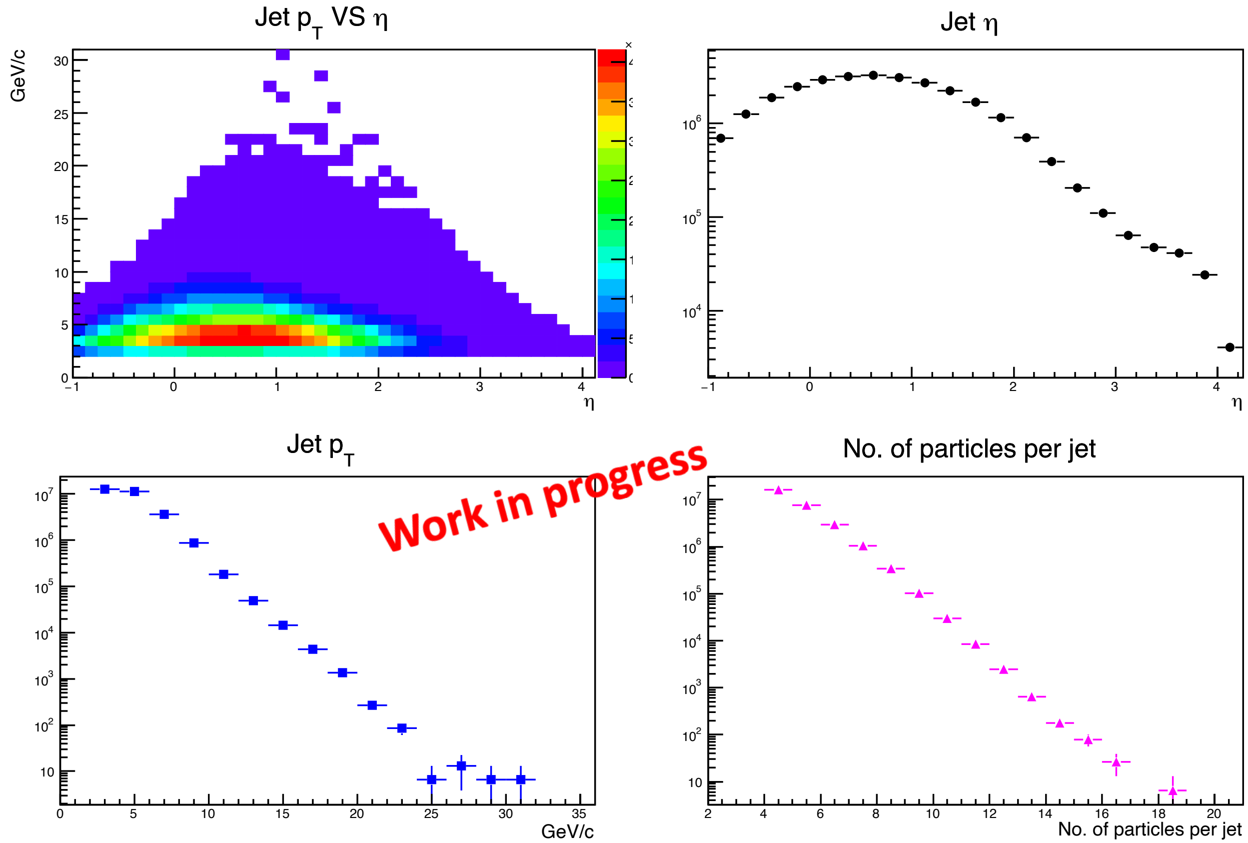


Arleo *et al.* PRC, 61 054906 (2000)

- Potential for decisive discrimination between different exotic structure models at the EIC.

Jet studies at the EIC

- The future EIC will be a jet factory.
- Kinematics of reconstructed inclusive jets in PYTHIA simulation.

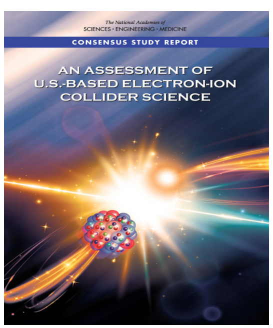


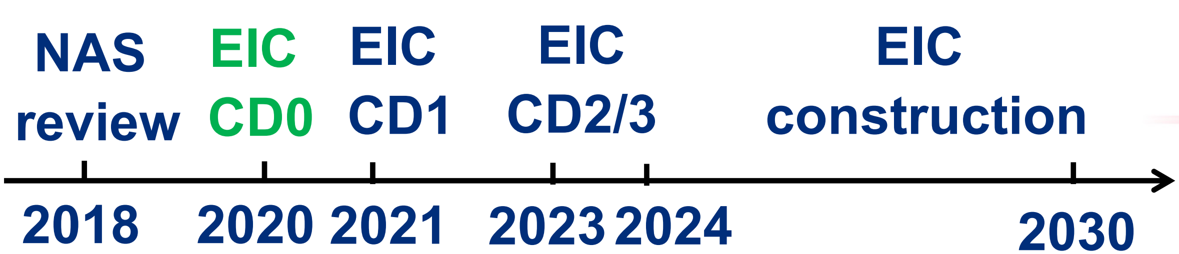
PYTHIA MC
E_e = 10 GeV
E_p = 100 GeV
anti-kT jet
algorithm R=1.0
$-1.0 < \eta < 4.0$
Int. Lumi.: 10 fb^{-1}

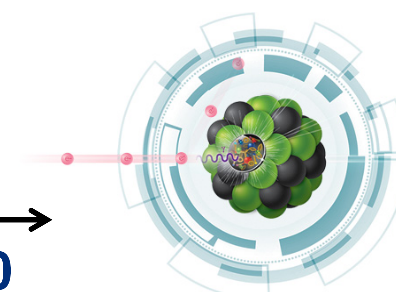
- Most jets produced at the EIC are with p_T < 20 GeV/c.
- Flavor tagged jets and jet substructure in e+p and e+A collisions to explore the hadronization processes are under study.

Summary and Outlook

- The new heavy flavor and jet program for the EIC will shed light into the flavor dependent energy loss and parton fragmentation processes in the poorly constrained kinematic region.
- Good precision in a wide kinematic coverage can be achieved by the future EIC heavy flavor and jet measurements that have been demonstrated in the initial simulation studies.
- We look forward to work with more collaborators and contribute to the EIC realization.



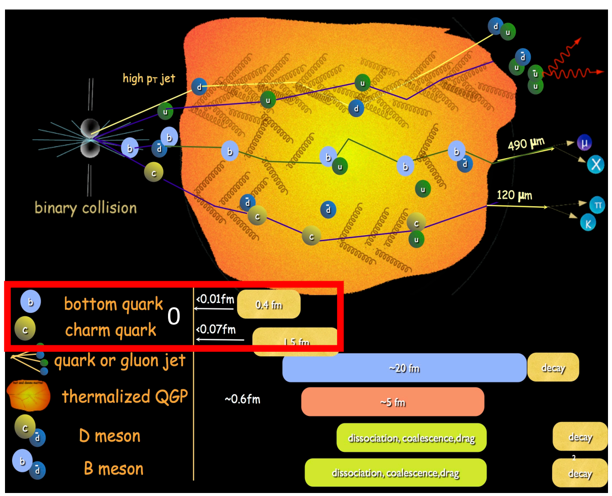




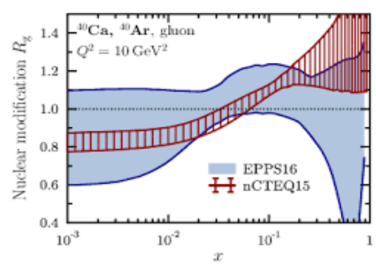
Backup

Motivation

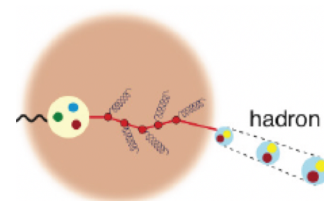
- Heavy flavor production is an ideal probe to study the full evolution of the medium as it is produced in the early stage of nuclear collisions due to its high mass ($m_c/m_b >> \Lambda_{QCD}$).
- Not well understood about interaction with the medium.
  - Cold Nuclear Matter (CNM) effects, e.g.: nuclear modification of PDFs, Cronin/EMC effects and …
  - Hot nuclear matter effects, e.g.: energy loss of partons traversing Quark Gluon Plasma (QGP), color screening and …



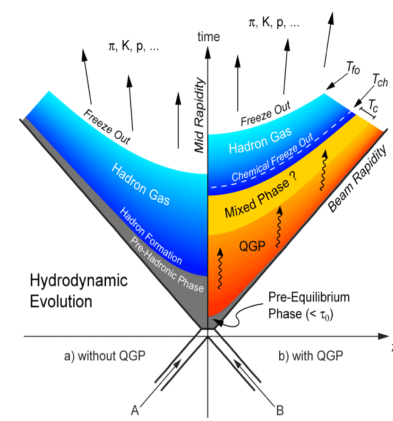
nPDF modification

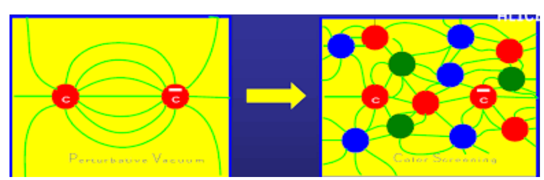


Parton energy loss



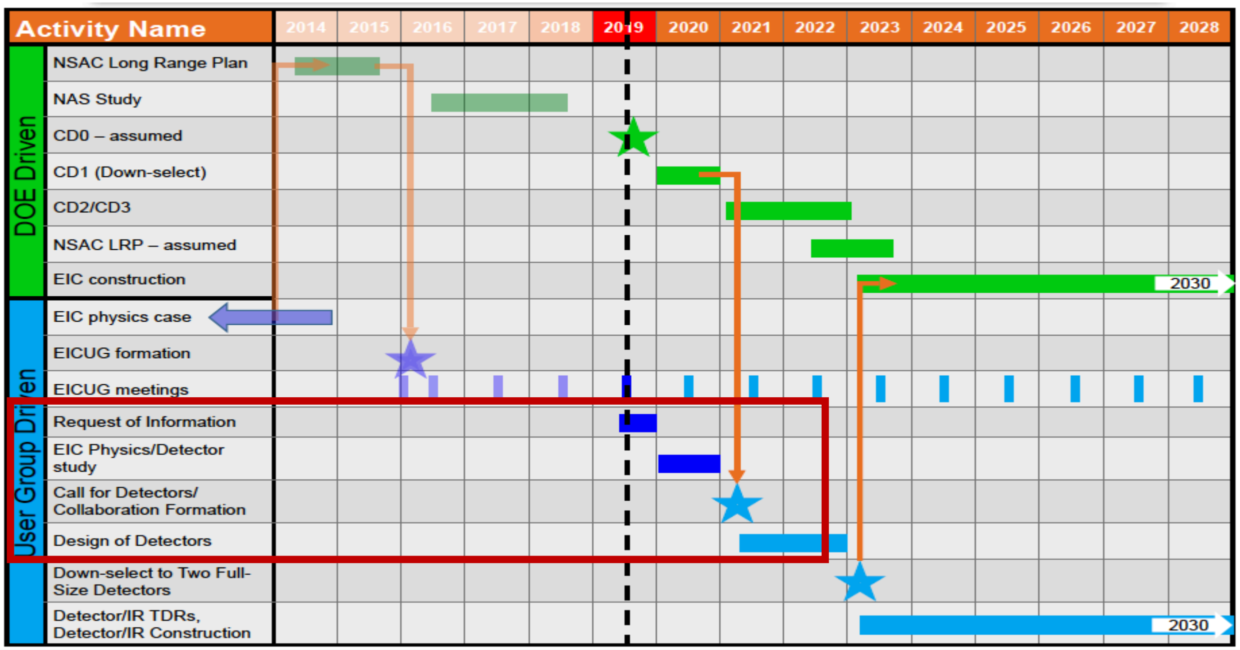
Parton transverse QGP



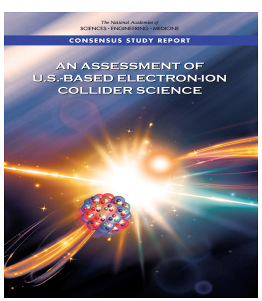


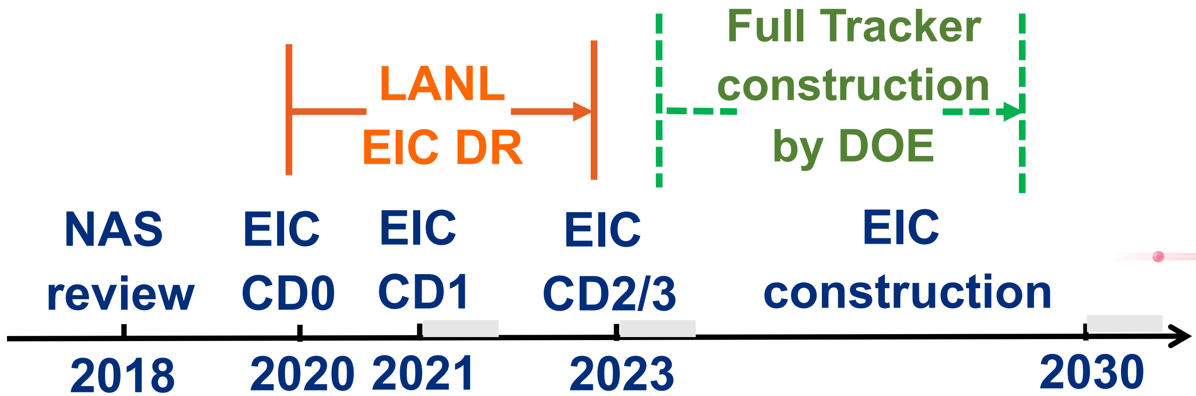
Color screening

The LANL EIC DR aligns well with the EICUG timeline

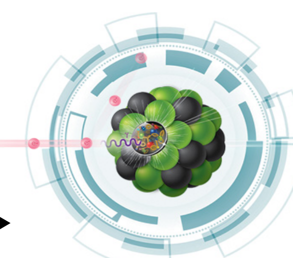


Updated DOE driven and User group driven timeline from the EICUG



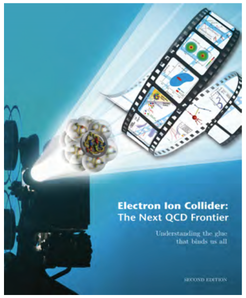


EIC operation

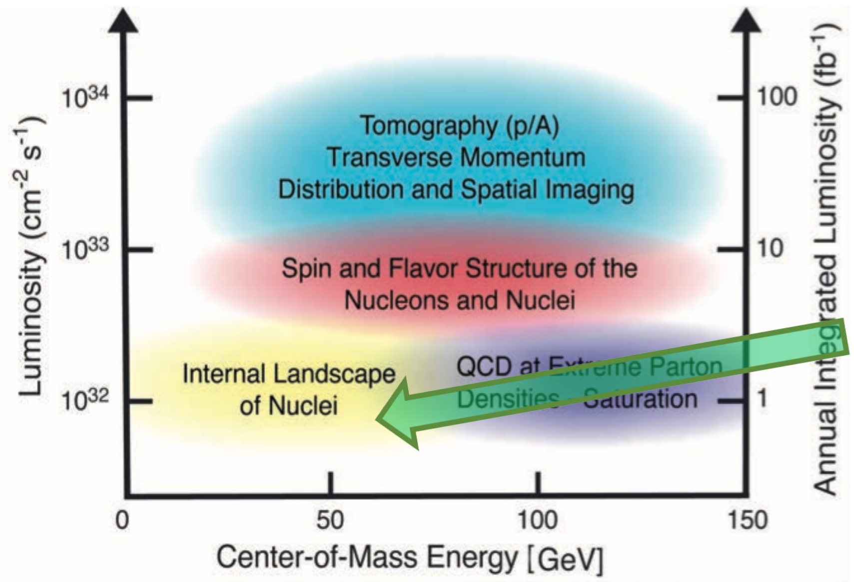


EIC science from the white paper

- EIC can help solve different fundamental physics problems in a wide x and Q^2 kinematic region.
  - How quarks and gluons distributed in momentum and space within the nucleon and heavy nuclei?
  - Proton spin origin?
  - What happens to the gluon density in nuclei, does it saturate at high energy?
  - A clean environment to study the hadronization and fragmentation process in nuclear medium.



A. Accardi et al, **Eur. Phy. J. A**, 52 9 (2016).

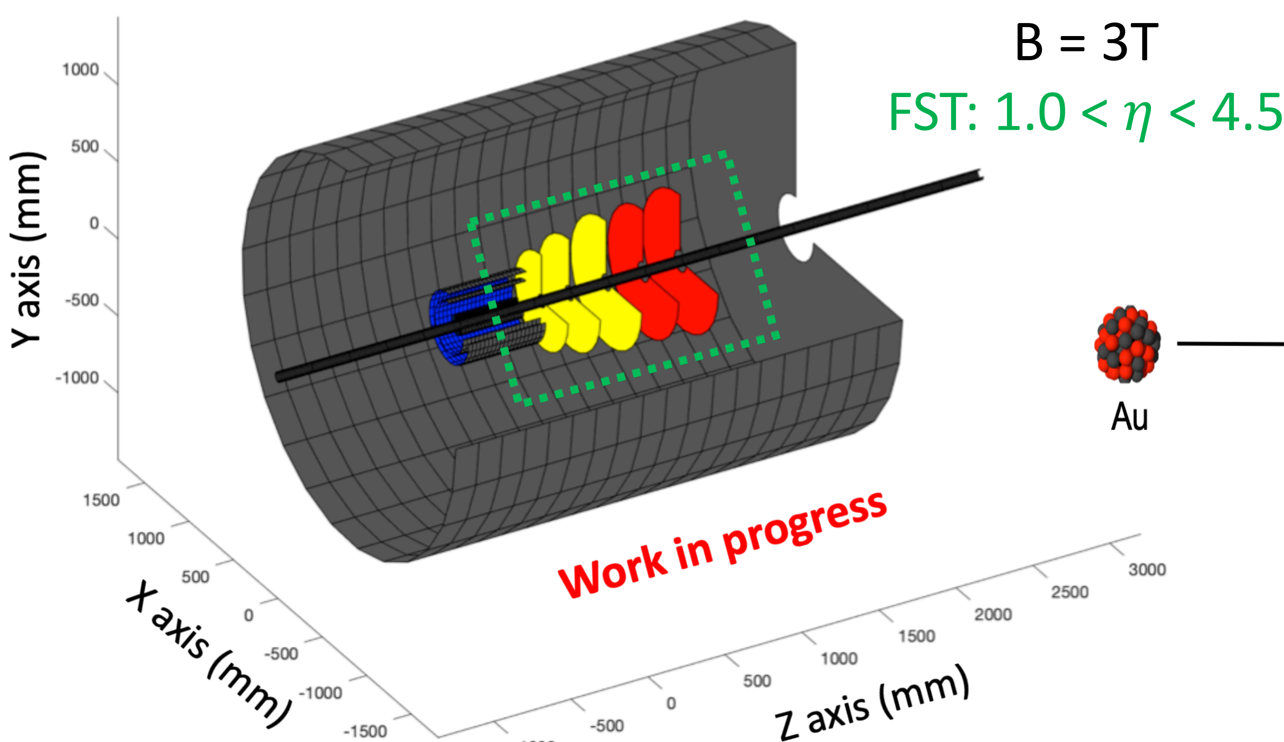


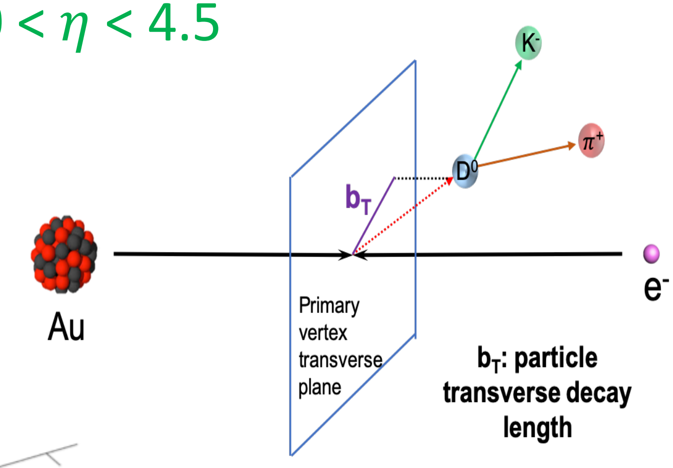
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

A new LDRD project funded by LANL with PI: Ivan Vitev, Co-PI: Xuan Li and 15+ staffs/postdocs has started to **develop a new heavy flavor and jet program for the future EIC and carry out relevant detector R&D.**

LANL EIC program progress – simulation studies (I)

- Detector design in fast simulation:
  - Assumed mid-rapidity silicon vertex detector: 5 barrel layers of Monolithic Active Pixel Sensor (MAPS) type detector.
  - Forward-rapidity silicon tracking detector (FST): 5 forward planes silicon detector. Update the geometry to leave space for the PID and calorimeter systems.

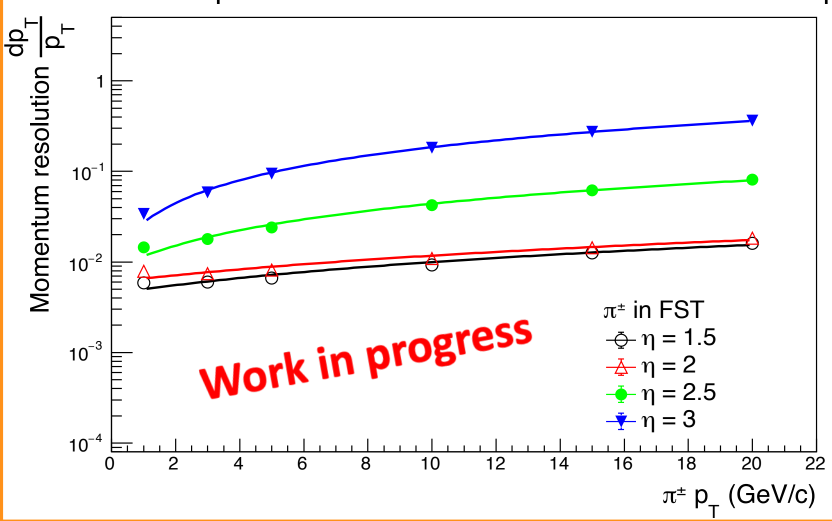




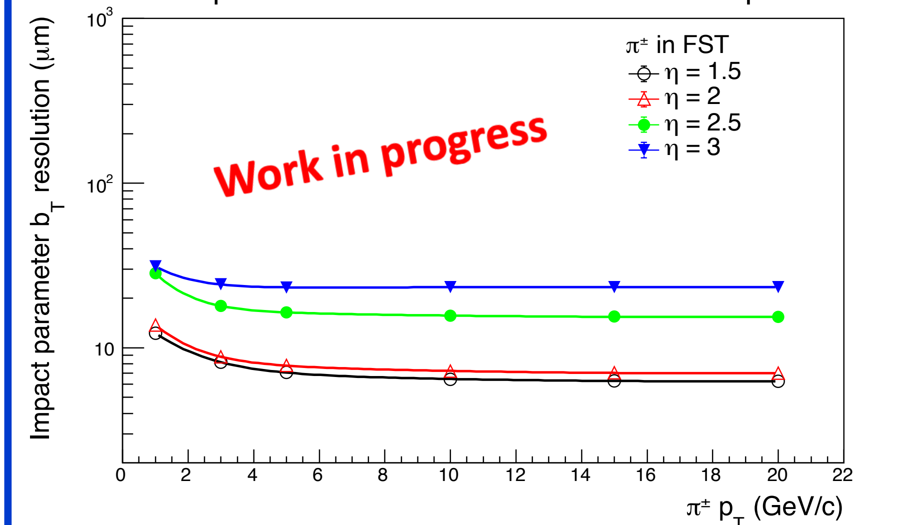
Reference run performance

- Track performance from the FST with pixel pitch 30 μm, materials per detector layer: MAPS 0.4%X_0 and HV-MAPS 0.8%X_0 and the readout rate is at 500 kHZ, same for the central barrel layers:

Projected p_T dependent momentum resolution dp_T/p_T



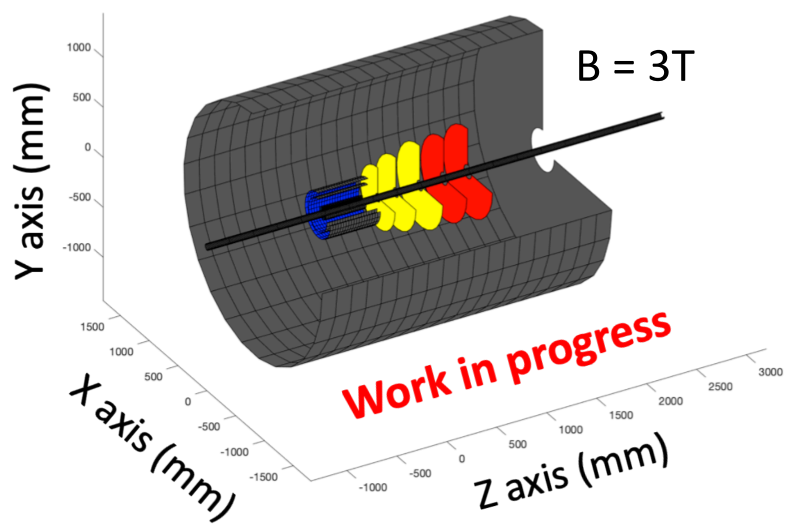
Projected p_T dependent impact parameter b_T resolution



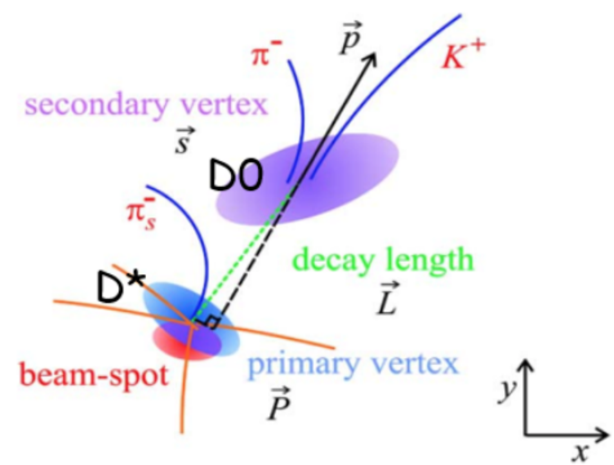
- Better than 40 μm resolution can be achieved by the initial FST design for the transverse decay length b_T measurements for tracks with p_T > 1 GeV/c over the 1.5<η<3.0 region.
- The momentum resolution dp_T/p_T are better than or consistent with the forward tracking requirements from the EIC detector handbook.

Simulation setup

- Updated central+forward silicon tracker detector design in fast simulation to evaluate the tracking performance, which will be used for smearing in generated events.

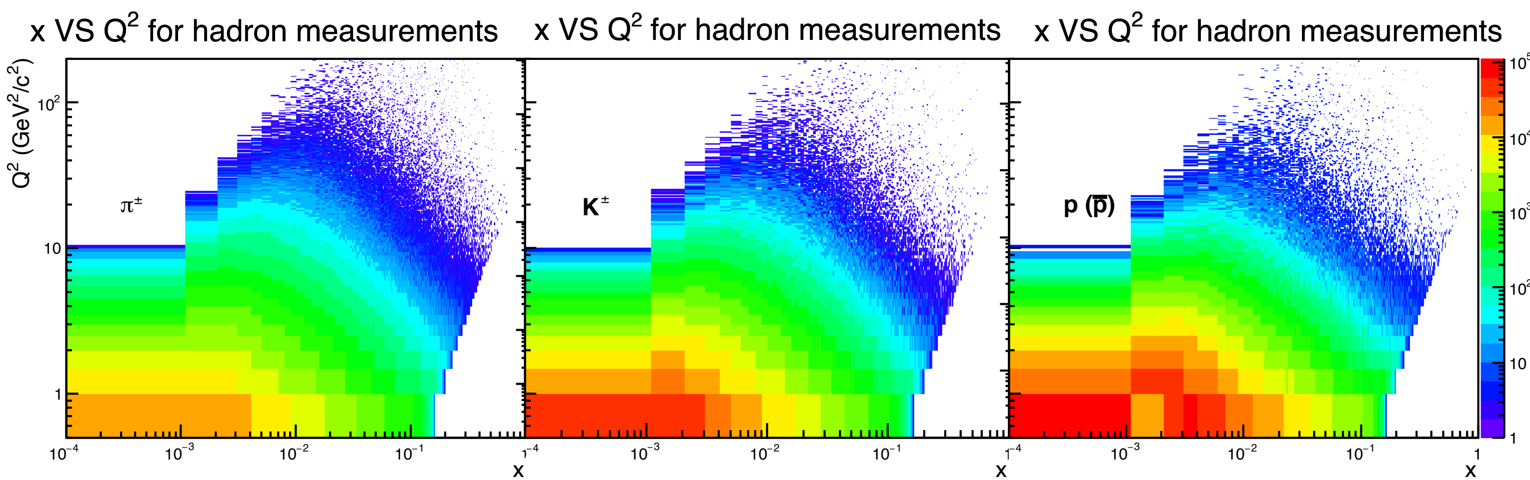


- The full analysis framework which includes the event generation (PYTHIA8), detector response in fast simulation, beam remnant interaction background embedding, and hadron reconstruction have been setup.
- Start with heavy flavor hadron reconstruction and we are working on the inclusive method as well.

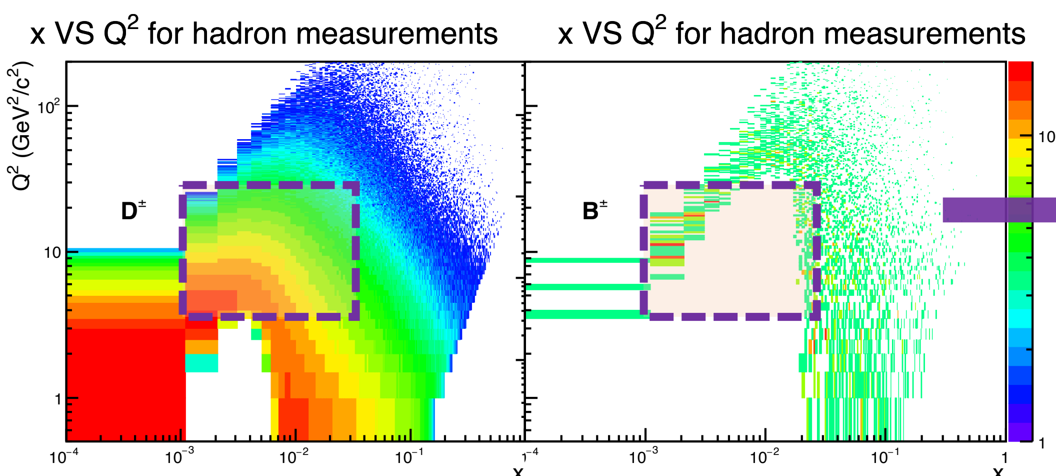


Future EIC measurements can access a wide kinematic phase space

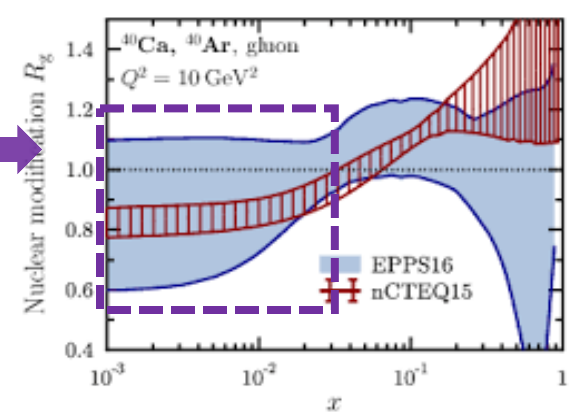
- Future EIC heavy flavor measurements can access the high x region and provide better constraints on the (nuclear) parton distribution functions in this region.



PYTHIA MC
E_e = 18 GeV
E_p = 275 GeV
Q^2_{min}=1GeV^2
Int. Lumi: 10 fb^{-1}

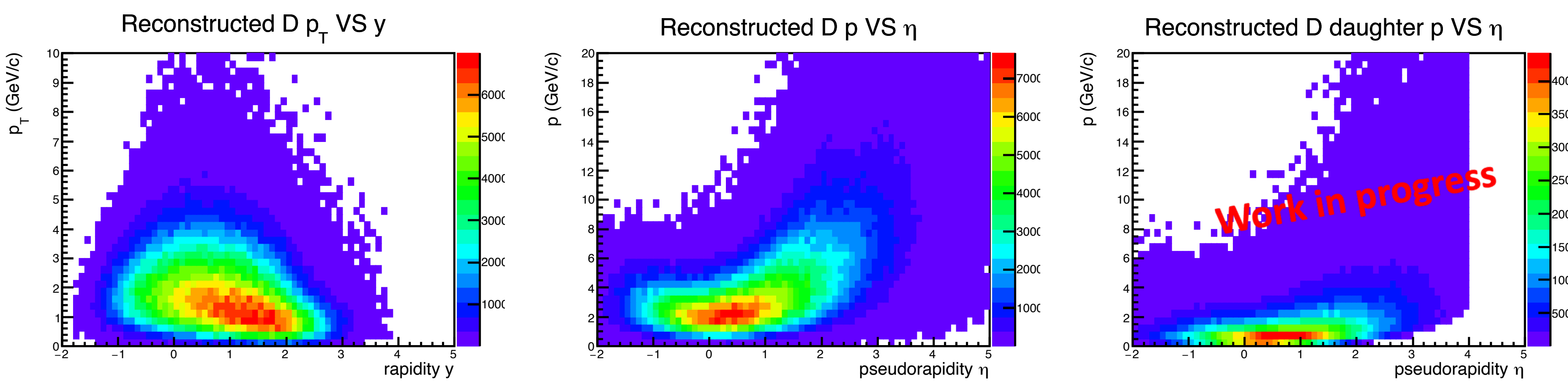


nPDF modification



Reconstructed D mesons in PYTHIA simulation

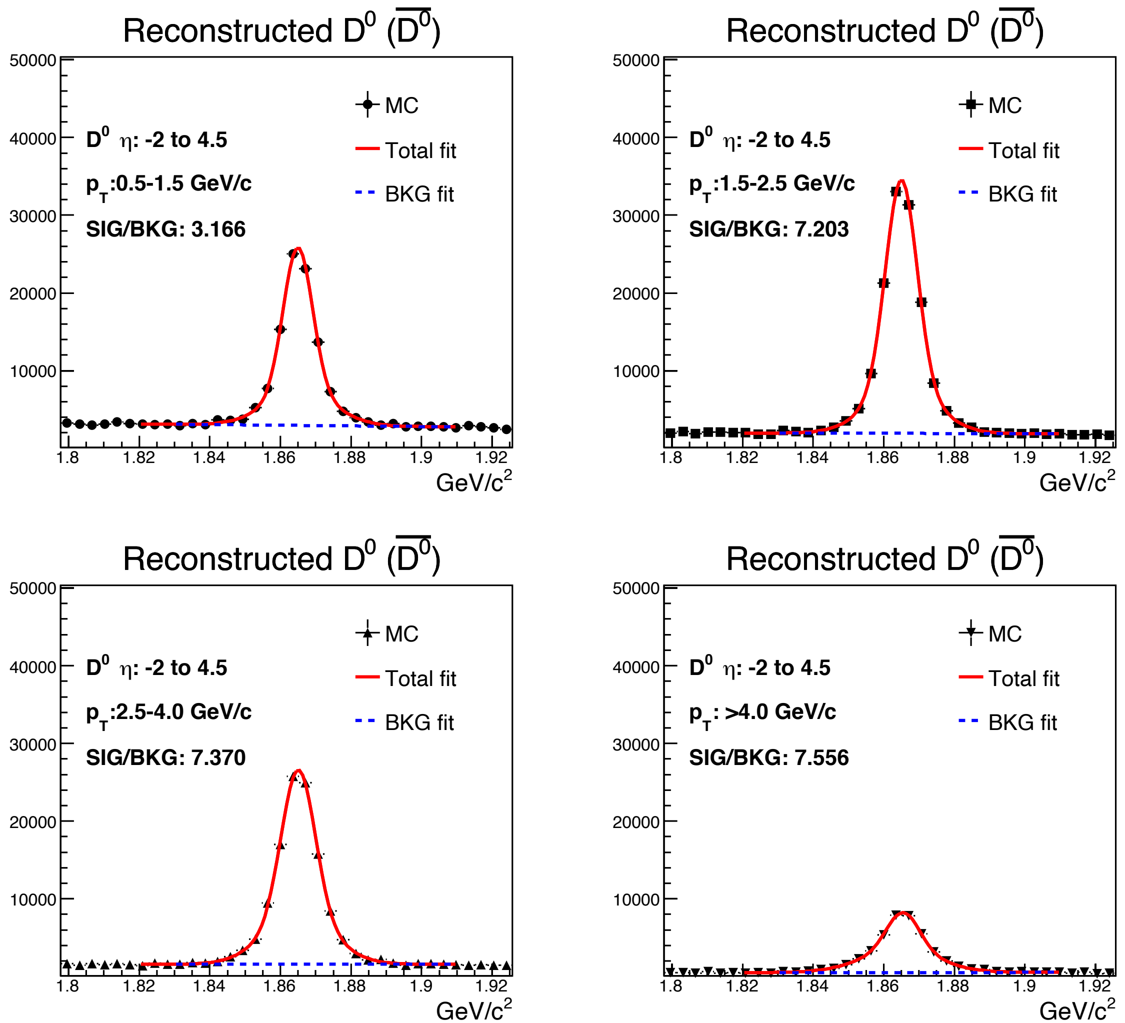
- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.
- Reconstructed D meson kinematic distributions:
  - Primary vertex resolution: 20 μm.
  - Tracking η cut: -2 to 4 and track efficiency set at 95%.
  - The performances are based on 80% K/π/p separation.
  - Reconstructed D-meson p_T VS rapidity (left), momentum VS pseudorapidity (middle) and the momentum VS pseudorapidity distribution for the D-meson decayed daughters (right).



- Most particles from forward D-meson decay have p<15 GeV/c.

Heavy Flavor reconstruction at the EIC

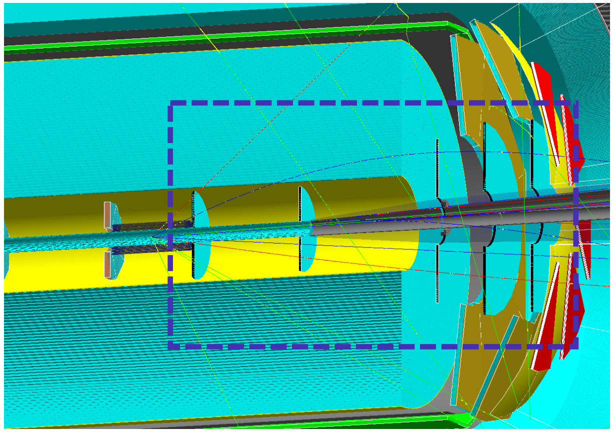
- Reconstructed D^0 ($\overline{D^0}$) meson mass distributions in different p_T regions.

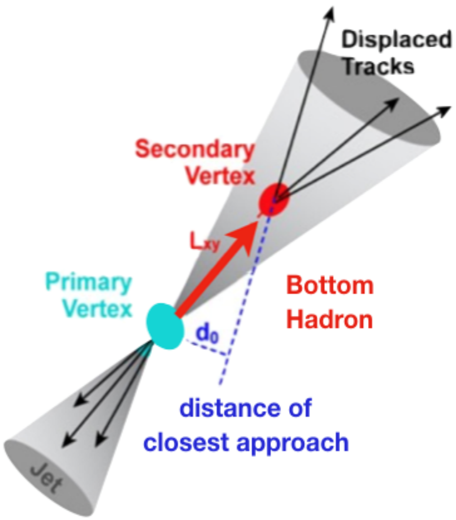


- Smaller signal over background ratio for lower transverse momentum D^0 ($\overline{D^0}$) reconstruction.

Open heavy flavor simulation plan

Initial design of the forward silicon tracker implemented into the Fun4All w/ Babar magnet.





- We have completed the projected stat. uncertainties for one of the golden measurements: flavor dependent R_{eA} for reconstructed hadrons with updated detector geometries.
- Implementing the updated vertex and tracking performance in the heavy flavor and jet studies is underway.
- Work on the projected stat. uncertainties of the nuclear modification factor R_{eA} with different collision energies, different kinematic regions is in progress.
- Will work on the flavor tagged jet cross sections and jet sub-structure studies in e+p and e+A collisions.